Analysis and Test Technology For Thin-Film Membrane Structures

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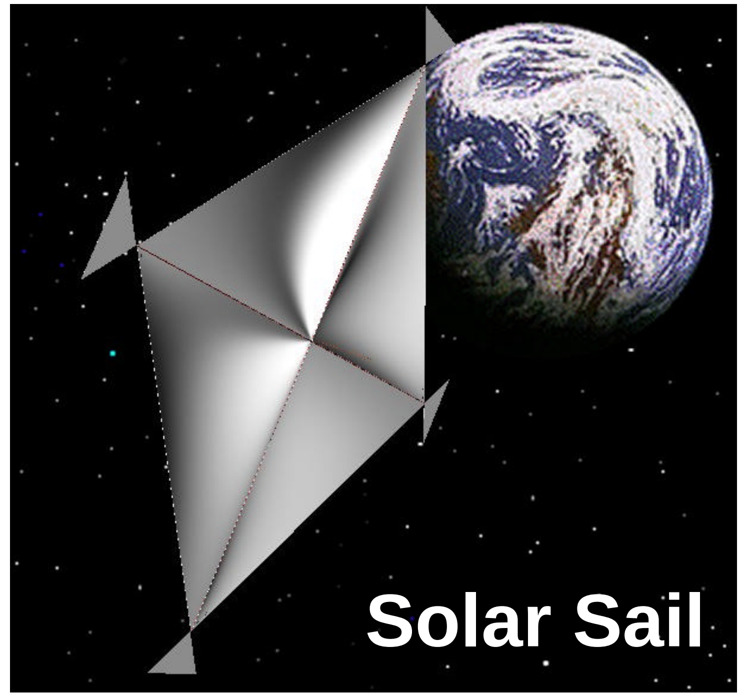
Motivation

- Very large, ultra-lightweight (so-called ‘gossamer’) spacecraft systems are considered to be an enabling technology for many future missions.

- Thin-film membrane structures are a common element in many of these systems. Examples include:
  - Solar sails
  - Sunshields
  - Membrane optics

- The development and validation of capabilities for analyzing and testing thin-film membrane structures is a challenging aspect of technology development for gossamer spacecraft.
  - Structural behavior, particularly wrinkling behavior, is highly nonlinear and difficult to predict.
  - Ground testing is complicated due to the influences of gravity, air, and instrumentation mass.

Applications of Thin-Film Membrane Structures



The Next Generation Space Telescope (NGST) requires a sunshield to passively cool it's optics. The sunshield consists of multiple layers of thin-film membranes supported by deployable booms.

Solar sails propel spacecraft by using very large membranes (on the order of 100's of meters in size) to harness the solar wind.

Needs and Objectives

- Technology Development Needs:
  - Modeling and Analysis
    - Capability to predict membrane wrinkling effects
    - Test validated structural modeling techniques
  - Testing
    - Advanced, non-contact measurement techniques
    - Scale model testing methodologies

- Research Objectives:
  - Develop advanced finite element modeling and analysis capabilities for wrinkled membrane structures.
  - Obtain benchmark test data for simple membrane structures.
  - Investigate non-contact measurement techniques for characterizing membrane behavior.
  - Validate modeling techniques through correlation of analytical models and test results from laboratory experiments.

Membrane Modeling and Analysis

- Summary of membrane modeling issues:
  - Modeling difficulties arise due to the negligible bending stiffness exhibited by thin-film membranes.
  - Preloading is required to develop out-of-plane stiffness in membranes and must be accounted for in dynamic analyses.
  - Wrinkles (local buckling of the membranes) can alter structural behavior and should be accounted for in static and dynamic analyses.

- Advanced techniques are required to model nonlinear aspects of membrane structural behavior.
  - Nonlinear analysis approach is required to accurately account for geometric nonlinearities (large displacements/rotations) and to include load stiffening effects.
  - Stein-Hedgepeth wrinkling theory can be used to account for effects of wrinkling on membrane behavior.

Membrane Wrinkling Theory

- Membranes, by definition, have zero (negligible) bending stiffness and cannot sustain compressive stresses.

- Compressive stresses are eliminated by wrinkling (out-of-plane deformations / local buckling).

- Stein-Hedgepeth Theory for Partially Wrinkled Membranes (1961)
  - Minor principle stresses are greater than or equal to zero everywhere in a membrane.
  - The stress state in a wrinkled region is uni-axial (positive major principal stress and zero minor principal stress).
  - Wrinkles form in straight lines along the direction of the major principal stresses (load transfer in the wrinkled region is along these lines).
  - The effects of wrinkling on the membrane structural response are accounted for using a variable Poisson's ratio that permits over-contraction in the direction of vanishing minor principle stresses in wrinkled elements.
  - The theory predicts *average* strains/displacements (not individual wrinkle details) in the wrinkled region.

Finite Element Analysis of Wrinkled Membranes

- Finite element implementation of Stein-Hedgepeth Theory
  - Miller-Hedgepeth (1982)
  - Adler-Mikulas (2000)

- The commercially available finite element analysis program ABAQUS was selected to perform the analysis.
    - ABAQUS has robust nonlinear analysis capabilities.
    - ABAQUS user material subroutines allow for the implementation of custom nonlinear constitutive relations.

- Wrinkling user material (UMAT) subroutine:
  - Iterative Membrane Properties (IMP) UMAT developed by Adler/University of Colorado-Boulder.
  - IMP UMAT subsequently modified at GSFC.

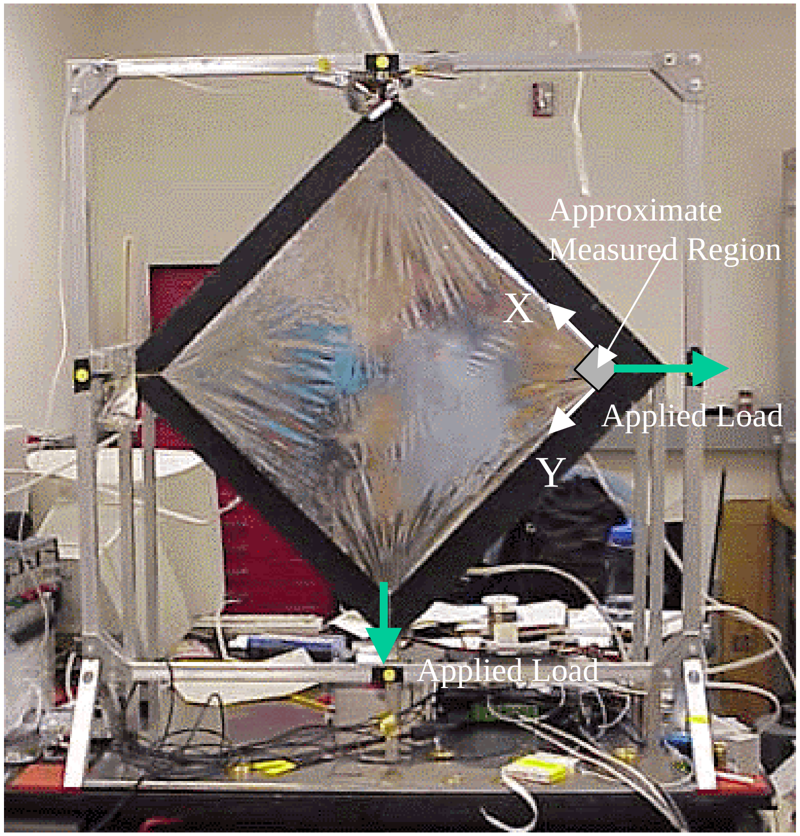
Analysis Procedure

- Summary of analysis procedure:
  - Create a finite element model using membrane elements that are assigned the IMP user material.
  - Perform a nonlinear static analysis to preload the structure.
    - During the analysis, the state of each element (integration point) is determined using the following criteria:
      - $\sigma_2 > 0 \rightarrow$ taut
      - $\varepsilon_1 \leq 0 \rightarrow$ slack
      - $\varepsilon_1 > 0$ and $\sigma_2 \leq 0 \rightarrow$ wrinkled
    - Modify the stiffness matrix for slack and wrinkled elements.
  - Perform additional quasi-static or dynamic analyses of preloaded structure.

- The analysis procedure is modified for combined loads (thermal and mechanical) cases.
  - Thermal analysis
  - Nonlinear static analysis
    - Step 1: Preloading
    - Step 2: Temperatures
  - Additional quasi-static or dynamic analyses

Application #1: Square Membrane

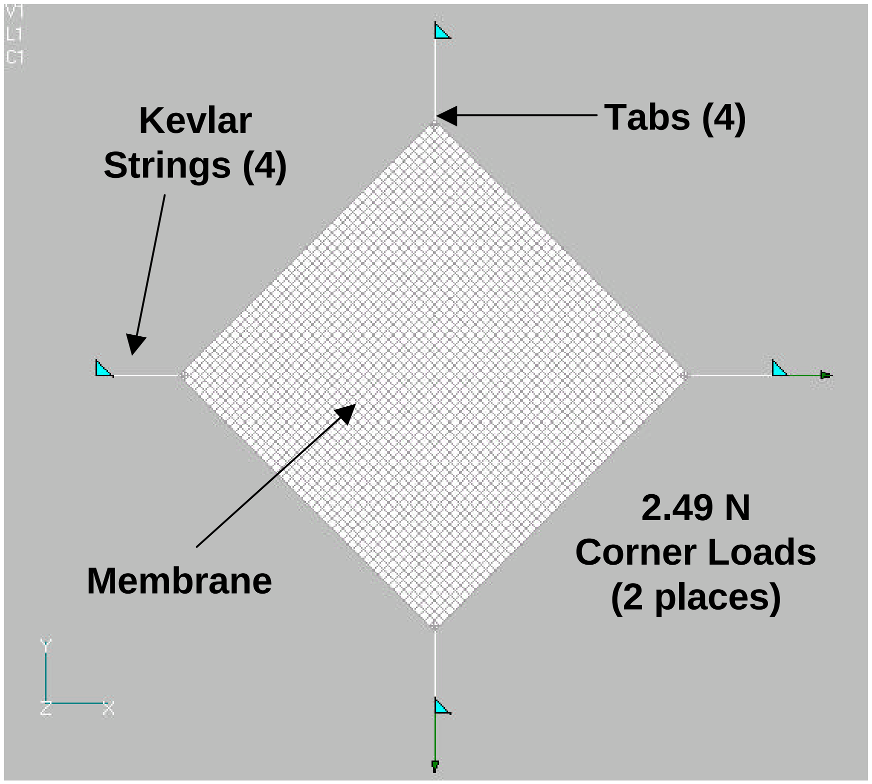
- A square membrane subject to discrete corner loads provides a simple case for studying wrinkling behavior in the laboratory.
- Test Article Characteristics:
  - Kapton membrane
  - Size: 0.5 m x 0.5 m x 1.27E-5 m
  - Vapor Deposited Aluminum coating
- The membrane is subject to both mechanical and thermal loads to study changes in the wrinkle pattern.
- Test results from the experiments will be utilized to validate analytical models of wrinkled membranes.



Photograph of James Madison University (JMU) Membrane Experiment

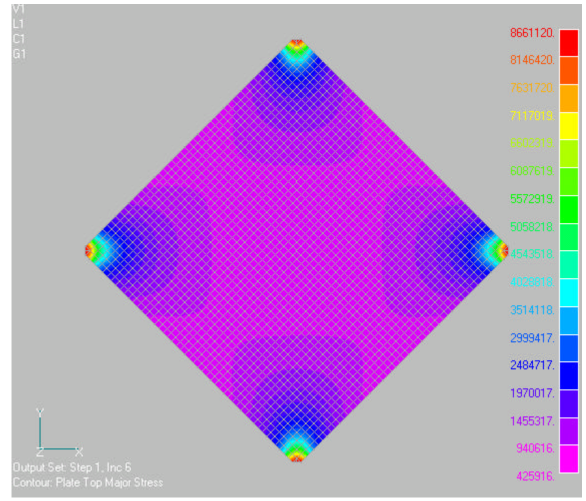
Finite Element Analysis

Finite Element Model

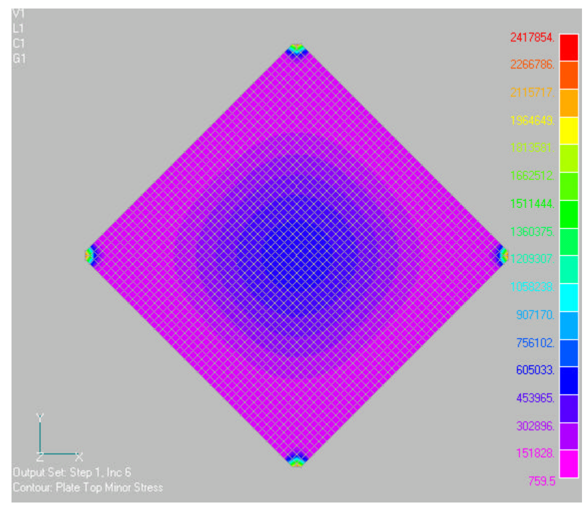


The finite element model uses a nonlinear constitutive relation to account for membrane wrinkling effects based on Stein-Hedgepeth theory.

Major Principal Stresses

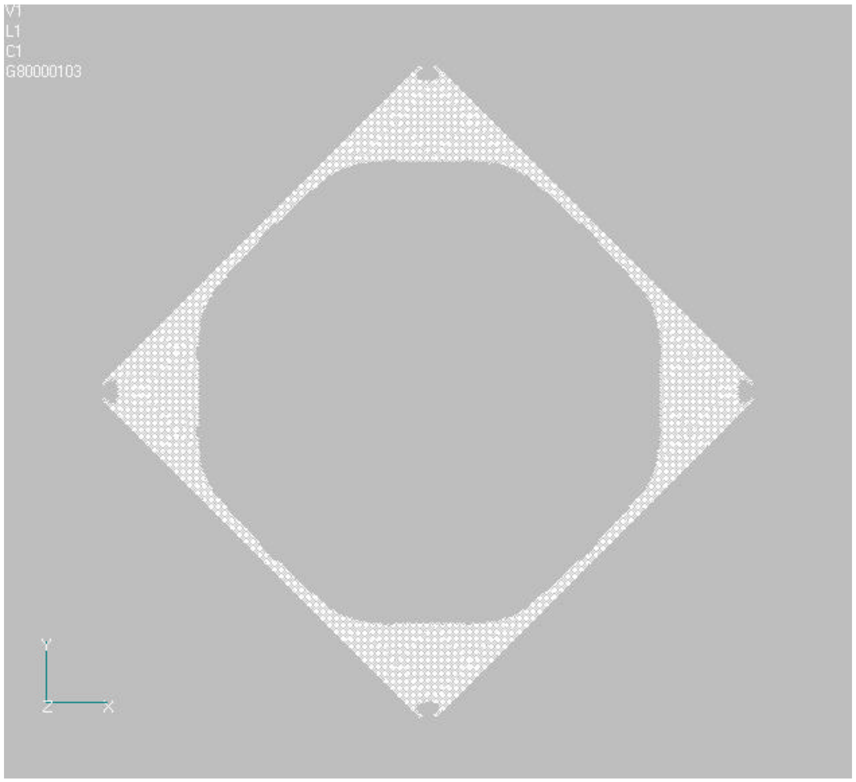


Minor Principal Stresses

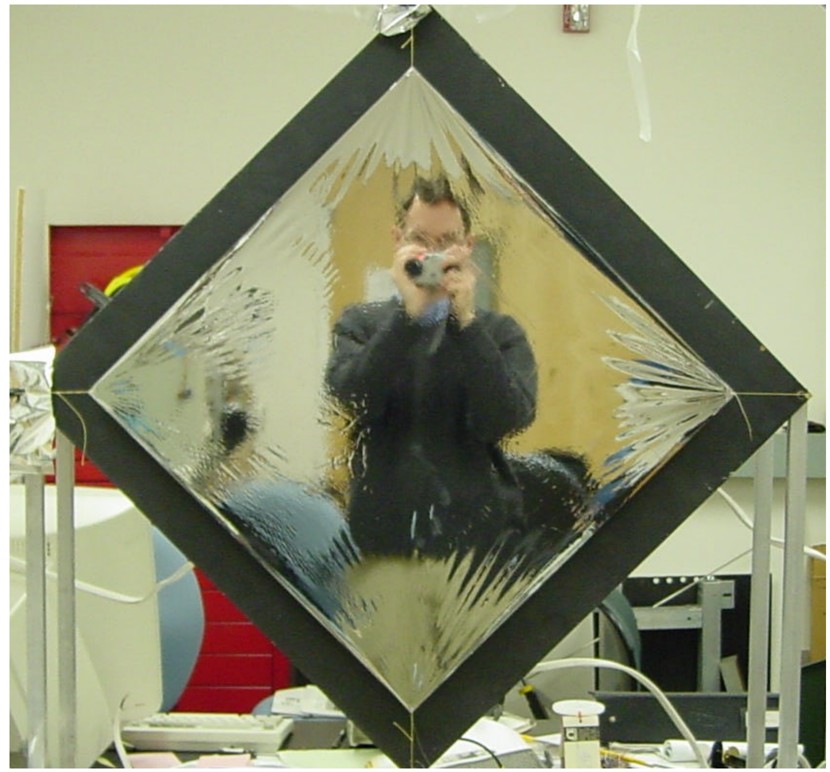


Wrinkle Region

FEA Prediction

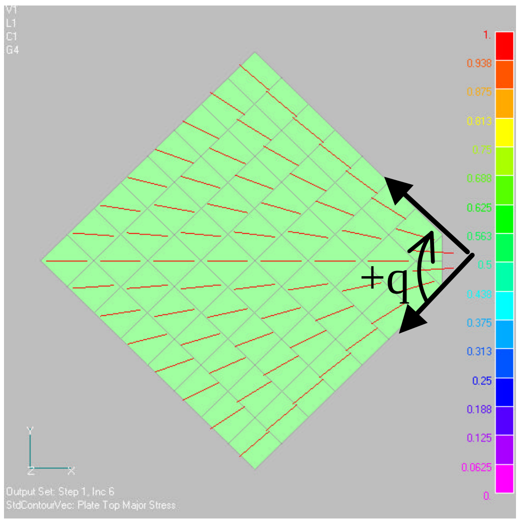


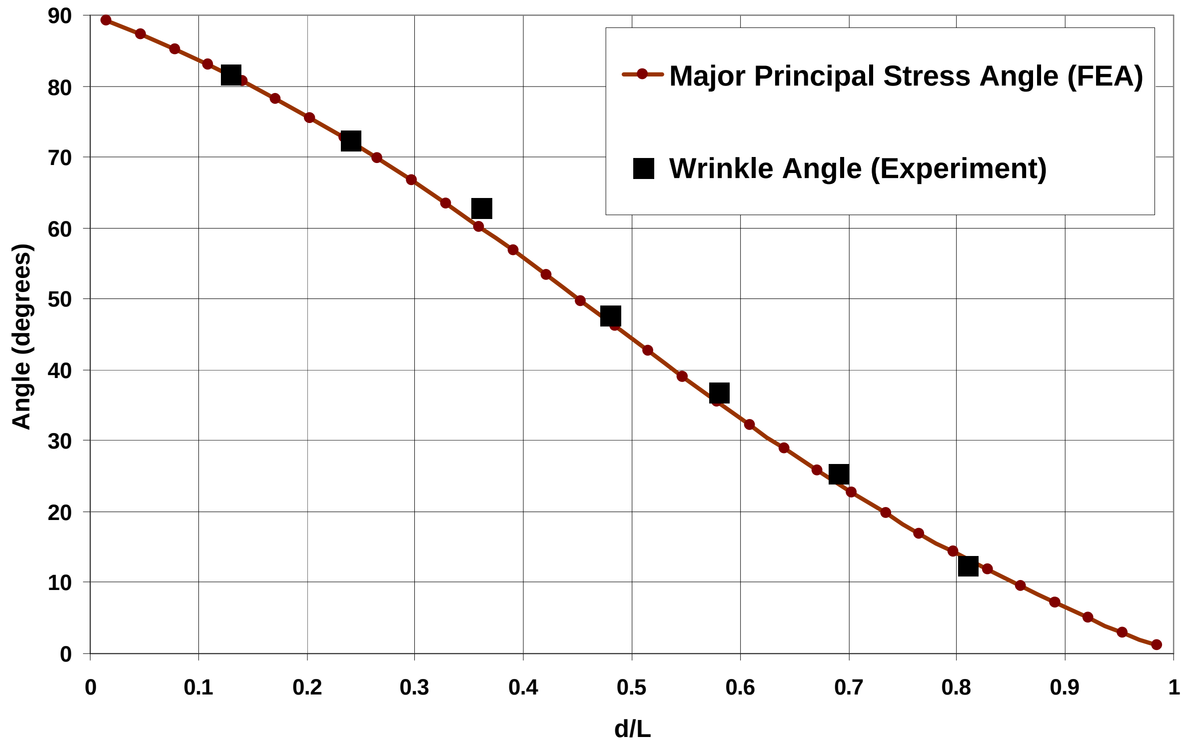
Photograph of Experiment



The wrinkled region extends from the load points at the corners and around the perimeter of the membrane, while the central region remains relatively flat and wrinkle-free. The location and size of the wrinkle region predicted by the finite element analysis shows good agreement with the wrinkle pattern observed in the laboratory.

Wrinkle Directions





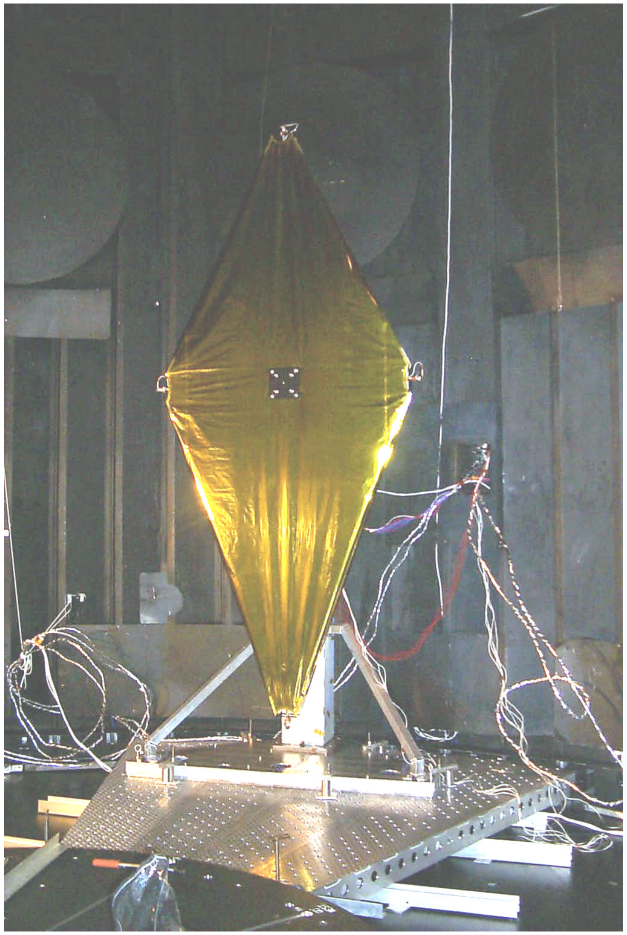
The plot presents a comparison of the predicted and measured wrinkle directions in the right-hand corner of the membrane. The directions of the wrinkles measured in the laboratory are aligned with the major principal stresses (as predicted by Stein-Hedgepeth theory).

Application #2:
One-Tenth Scale Model NGST Sunshield

- Analysis and ground testing of a one-tenth scale model of the NGST ‘yardstick’ concept sunshield is being carried out to develop and validate capabilities to predict and verify sunshield structural characteristics.

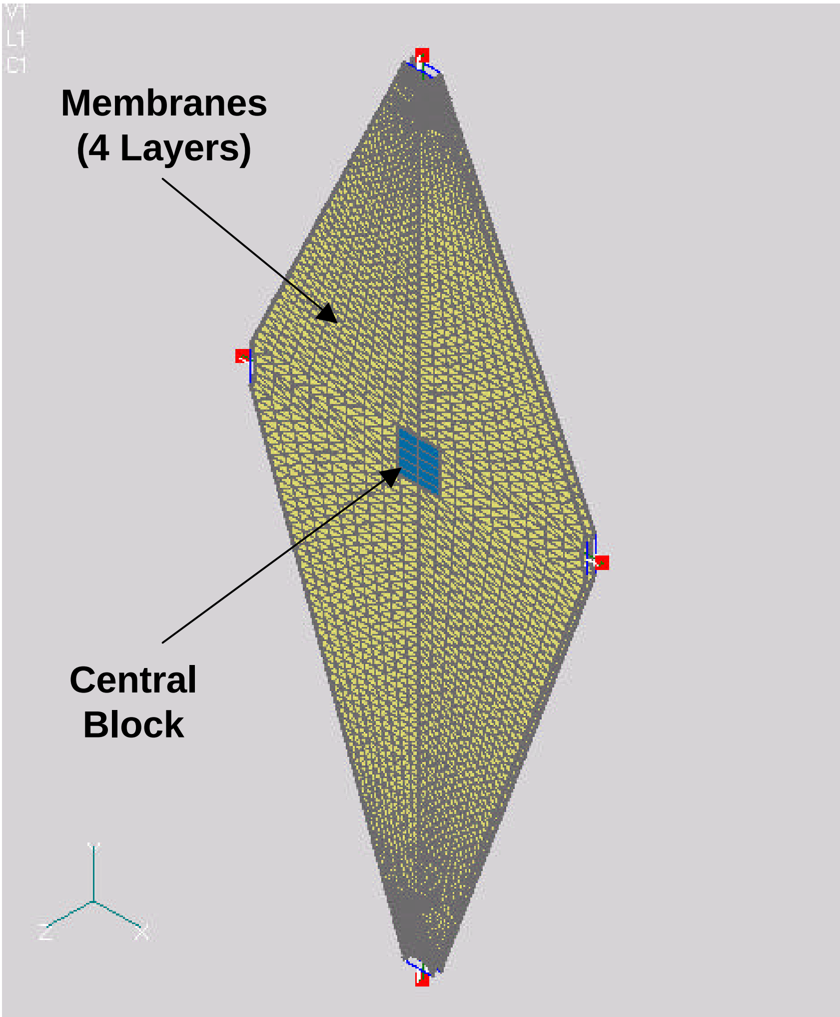
- Test Article Characteristics:
  - Overall size: 3.4 m x 1.52 m
  - Kapton Membranes
    - 4 layers
    - 13 micron (0.0005 in.) thickness
    - Preload: 1.425 N (0.32 lbs)
  - Aluminum Support Tubes

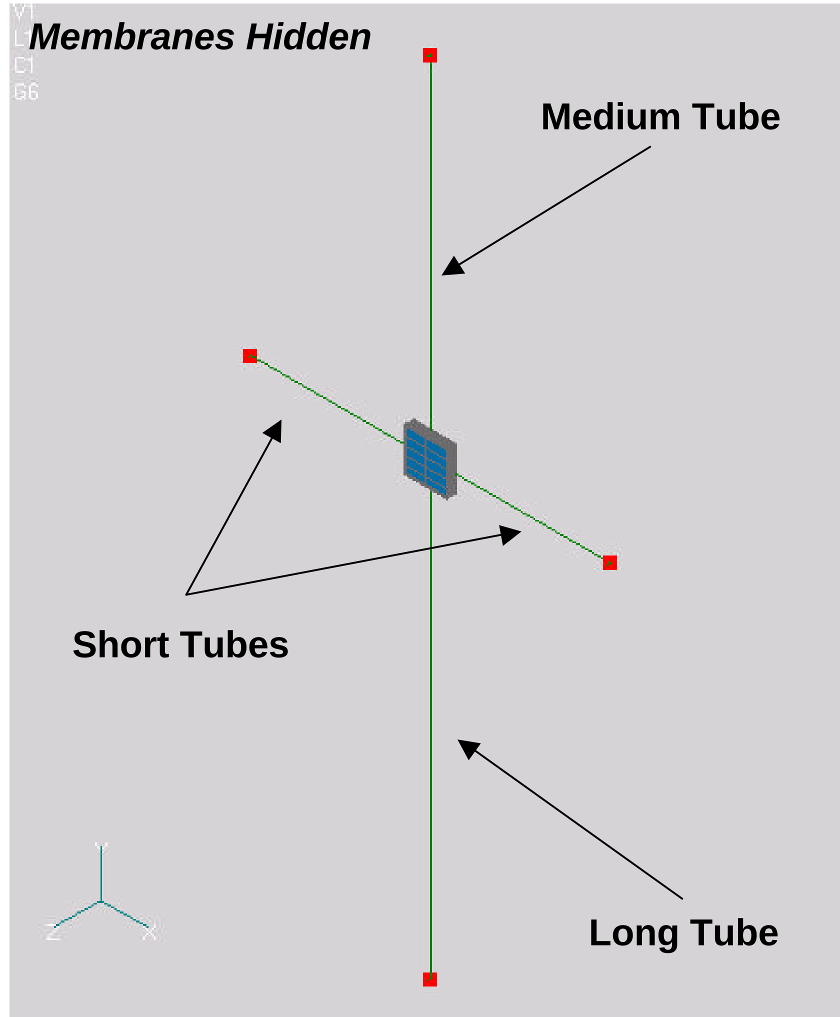
- Dynamic testing of the one-tenth scale model NGST sunshield in a vacuum environment was completed in August 2000 at NASA GSFC.



Photograph of One-Tenth Scale Model NSGT Sunshield

Finite Element Model





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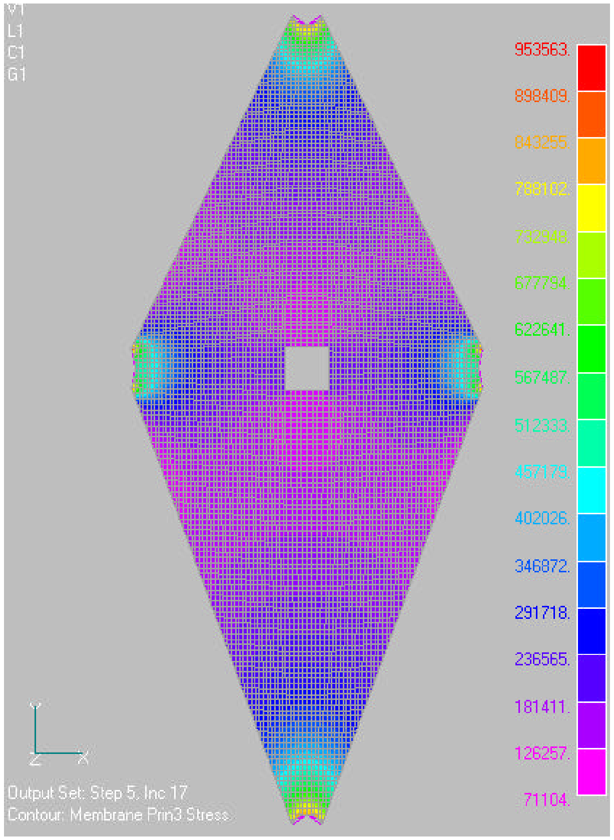
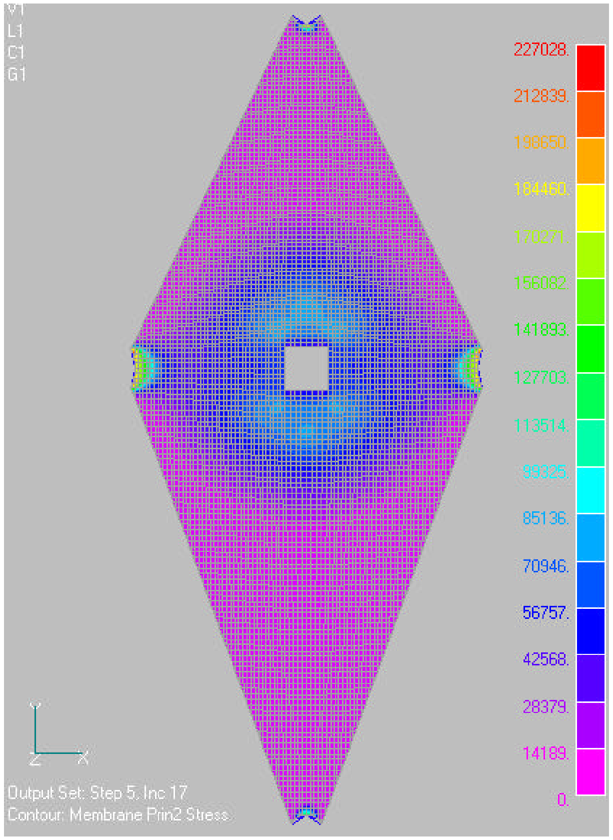
Membrane Stress Analysis

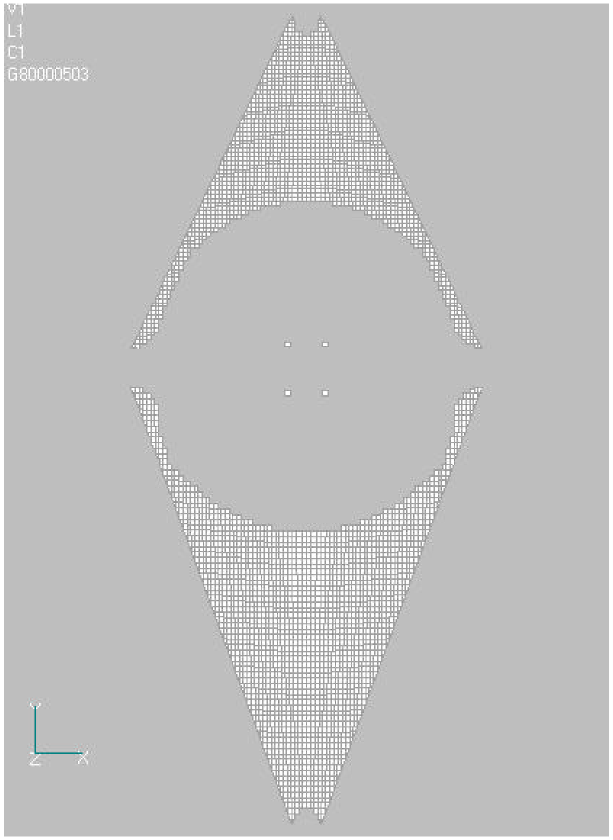
Major Principal Stresses



Minor Principal Stresses



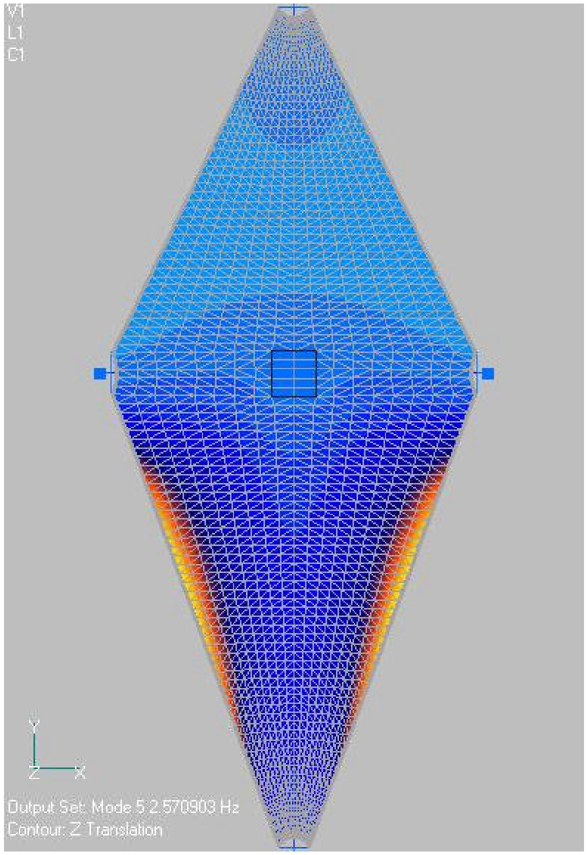
Wrinkle Region



A nonlinear static analysis is performed to predict the response of the sunshield to preloading from the constant force springs. The plots depict the principal stress distributions and the predicted wrinkle region in a single flat membrane layer.

Sunshield Dynamics

$F_{predicted}$ = 2.6 Hz



$F_{measured}$ = 2.7 Hz

A modal analysis is performed to calculate the natural frequencies and mode shapes of the sunshield. The plots depict the predicted and measured out-of-plane displacements for a vibrational mode primarily involving the long side of the membranes.